FEM Modeling of a 3D Printed Carbon Fiber Pylon

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Abstract: The evolution of specific three dimensional (3D) printing fabrication technologies has developed the capability to fabricate functional parts in several fields of the engineering. The aim of this study is to evaluate the elastic properties of 3D printed carbon fiber pylon under compression stress and compare them with experimental data, in order to estimate its properties and allow mechanical analysis by computational tools. 3D printed polymeric samples are fabricated through a continuous fiber fabrication (CFF) process. The principal elastic modulus E_Z and E_y are obtained by developing experimental tests under ASTM D695 standard. The shear modulus is computed from the composite theory, by managing specific values of the Poisson ratio. The modeling work in COMSOL Multiphysics 5.2a is developed under static conditions, using the Solid Mechanics module. The CAD geometries of the printed pylon are created in Solid Works and then imported to COMSOL. Two different CAD models are designed: the first one is a laminated specimen, while the second one is a solid orthotropic material. Appropriate boundary conditions are set in order to model the experimental condition. Then, by developing the simulation work with COMSOL Multiphysics, a simple mechanical performance of the pylon is simulated.

Keywords: carbon fiber pylon, solid mechanics, compression stress, FEM.

1. Introduction

Additive Manufacture Technology provides the possibility to work with many polymers, although a few ones can be used as functional parts in engineering applications, because these materials are not enough resistant for a final product (Domingo-Espin *et al.*, 2015). Improvements on Fused Filament Fabrication (FFF) technology have allowed the possibility to fabricate parts by continuous fiber reinforced polymers and additive manufacture technologies. Another process like the CBAM has the possibility to create parts, based on thin carbon layers and polymers. The fabrication of fiber reinforced polymer (FRP), by 3D printing technologies, provides the possibility to improve the mechanical properties of the material used in additive manufacture. However, the implementation of functional part fabricated by 3D printing technologies is difficult, because several factors affect the mechanical properties of these parts (Domingo-Espin et al., 2015; Wu *et al.*, 2015). To ensure the mechanic resistance of 3D printed parts, it is necessary to evaluate the mechanical properties of the material under end-use mechanism loads (Domingo-Espin, *et al*, 2015; Sutradhar *et al.*, 2014).

The mechanical behavior of 3D printed parts has been studied by FEM (Domingo-Espin *et al.*, 2015; Sutradhar *et al.*, 2014; Góski *et al*., 2015; Sayre, 2014). Domingo-Espin *et al* (2015) concludes what the if the polymeric material does not exceed the yield stress, it can be considered as isotropic. But, to evaluate a FEA model of 3D printed FRP parts is necessary to assume a no homogeneous material, because the reinforce fiber produces specifics effect on the mechanical behavior (Mallick, 2008).

In this paper we develop an experimental work to evaluate the compression properties of 3D printed carbon reinforced parts and a successive computational work to simulate the mechanical performance of the 3D printed prosthetic pylon of Fig. 1. In the next sections, a brief introduction concerning the property of the pylon is given at the beginning, followed by the description of the experimental and

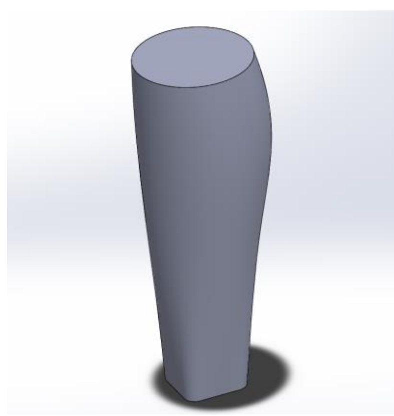

Figure 1. Schematic of the prosthetic pylon.

computational works. Finally, the results obtained in our work are presented and analyzed.

2. Theory

The direction of the reinforce fiber is the principal factor affecting the mechanical properties of reinforced parts (Mallick, 2008). It is important to define bidirectional reinforced architecture on fabricated parts to improve the performance of parts in two directions. In order to study the mechanical behavior of 3D printed reinforced parts by FEM, it is important to consider the orthotropic characteristic of the reinforced polymers. In some cases, it could be necessary to determinate the nine engineering elastic constants of materials. However, fabrication process can configure bidirectional reinforced on the *xz* plane, where the *z* orientation is normal to the figure plane in Fig. 2. This configuration produces a mechanical equivalence on *z* and *x* direction (Mallick, 2008; Domingo-Espin *et al*., 2015). To determinate some

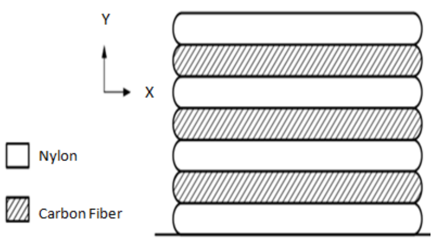

Figure 2. Example of a layer configuration of 3D reinforced part.

mechanical properties that cannot be measured by experimental test, it is possible to use analytical and mathematical approximations under the mixture law (Mallick, 2008). Orthotropic materials are defined by three mutually perpendicular symmetry planes. By analyzing the mechanical behavior of materials under elastic strain, the mechanical performance is defined by the compliance matrix, which is written in terms of Young´s modulus, Poisson´s ratio and shear modulus by (1) (Domingo-Espin *et al*., 2015):

$$\begin{matrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{zy} \end{matrix} = \begin{matrix} 1/E_x & -\upsilon_{xy}/E_x & -\upsilon_{xz}/E_x & 0 & 0 & 0 \\ -\upsilon_{xy}/E_x & 1/E_y & -\upsilon_{yz}/E_x & 0 & 0 & 0 \\ -\upsilon_{xz}/E_x & -\upsilon_{yz}/E & 1/E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{yz} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{xz} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{xy} \end{matrix} * \begin{matrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{zy} \end{matrix} \quad (1)$$

To evaluate the bidirectional reinforce material, at least two Young´s modulus (E_{ij}), two Poisson´s ratio (υ_{ij}) and two shears modulus (G_{ij}) must be found (Mallick, P. 2008).

3. Experimental work

As our focus is the mechanical compression of reinforced polymer, three different samples are evaluated under compression stresses. Sample dimensions are 12x12x24 mm, fabricated with the A and B orientations of Fig. 3, with 100% in-fill, 0.125 mm of layer thickness and concentric fiber reinforced on approximately 30% of layers. Supplier configurations of temperature and velocity of the print process are used. Following the ASTM D695 standard for compression properties of reinforced polymers, we test three different specimens with the A and B orientations of Fig. 3.

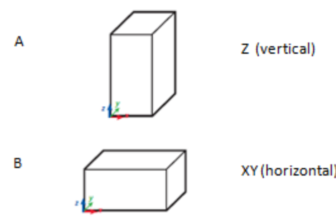

Figure 3. Sample orientations evaluated.

Mechanical tests in A and B direction provide the E_z and E_y modulus of the material. Then, it is possible to determinate the shear modulus and Poisson´s ratio by the mathematical approximations (2) and (3):

$$G_{xy} = \frac{E_{xx}}{2(1+\upsilon_{xy})} \quad (2)$$

$$\upsilon_{xy} = -\frac{\varepsilon_{xx}}{\varepsilon_{yy}} \quad (3)$$

Compression tests follow the ASTM D695 standard requirements. We use a Tinius Olsen equipment with a load of 50 kN and a velocity load of 1.3mm/seg. The Young´s modulus is computed by the slope of the linear plot in the elastic region.

4. Computational work

Using COMSOL Multiphysics 5.2a, we develop a stationary study of the 3D pylon using the Structural Mechanics module and analyzing only the linear elastic behavior. A first FEM model assumes an isotropic material while a second one considers a laminated material fabricated by polymer matrix and thin fiber layers of carbon fiber, with isotropic properties. Finally, a third model analyses a solid orthotropic material with properties of an orthotropic composite material. In order to simulate the experimental compression test, we prescribe displacements equal to zero in the z direction for the lower boundary of the sample part (Fig. 4). Also, we use a fix constrain in the upper part of the disc base. We apply a force of approximately -5840 N in the z direction on the upper side of the sample. With this total force, we should simulate the experimental yield stress of the material, which is 42 MPa approximately.

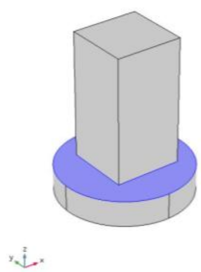

Figure 4. Boundary constraints.

Initially, an isotropic model material is simulated with a Young´s module equal to E_z (Table 1). Then, a second CAD laminated material model is evaluated with two different properties, calculated by the mixture law, given the volume of each constituent material (30% carbon fiber, approximately). In this case, polymer matrix and carbon fiber were defined as isotropic materials. The material properties of the polymer matrix have been obtained by the mechanical test, while the carbon fiber properties have been deduced by the mixture law (Table 2). A second model for the laminated material simulates a reinforced material by thin layers. Hence, we use the mixture law to define the Young modulus of matrix and fiber components. In the model each material is defined as isotropic. A third model with an orthotropic material has been developed using the orthotropic constants obtained by experimental and mathematical methods, which are given also in Table 1.

Using COMSOL Multhiphysics 5.2a we simulate the mechanical tests, using experimental (E_{ij}) and analytical (υ_{ij}, G_{ij}) mechanical properties. The simulations are designed by applying a force equal to the force achieved in correspondence of the experimental yield point of the mechanical test. The three different materials have been modeled and evaluated under same mechanical conditions. Finally, two different reinforced materials have been simulated.

Table 1: Estimated material properties of the isotropic material.

Young modulus	Magnitude
E_y	0.7393 [GPa]
$E_z = E_x$	1.911 [GPa]
$\upsilon_{yz} = \upsilon_{xz}$	0.4
υ_{xy}	0.4
G_{xy}	0.2640 [GPa]
$G_{yz} = G_{xz}$	0.6825 [GPa]

Table 2: Polymer matrix and carbon fiber (C.F.) mechanical properties.

Properties	Matrix	C.F.
Young modulus	0.6579 [GPa]	6.087 [GPa]
Poisson ratio	0.4	0.1
Shear modulus	0.2350 [GPa]	2.767 [GPa]
Yield	26.35 [MPa]	79.98 [MPa]

5. Experimental results

The Young modules measured by experimental tests are shown in Table 1 for the three directions. The Poisson ratios are approximated by Eq. (4), with the strains at 10 MPa ($\varepsilon_{10.i}$) and 15 MPa ($\varepsilon_{15.i}$):

$$-\upsilon_{xy} = \frac{\Delta\varepsilon_x}{\Delta\varepsilon_y} = \frac{(\varepsilon_{15.x} - \varepsilon_{10.x})}{(\varepsilon_{15.y} - \varepsilon_{10.y})} \quad (4)$$

The method provides us only with the υ_{xy} Poisson ratio, hence we have supposed the same value in all the directions. The shear modulus is computes by Eq. (2), using an estimated Poisson ratio.

6. Computational results

Using the values of Table 1, the computational result for the isotropic material is quite different from the experimental value of the yield, which is 42.97 MPa.

Then, by modifying the Poisson ratio until the value of 0.025 and using the same values of *E* and *G* of Table 1, the simulation results performed better with a relative error of 3%, approximately. Table 3 gives the FEM results, the experimental stress at the yield point and the relative error for the isotropic model with υ_{ij} = 0.025.

Table 3: Experimental and computational results for the isotropic material.

FEM [MPa]	**Yield** [MPa]	**Relative error**
44.3	42.97	3.09%

Figure 5 shows the von Mises stress (44.3 MPa) generated under forces at the yield stress of the material.

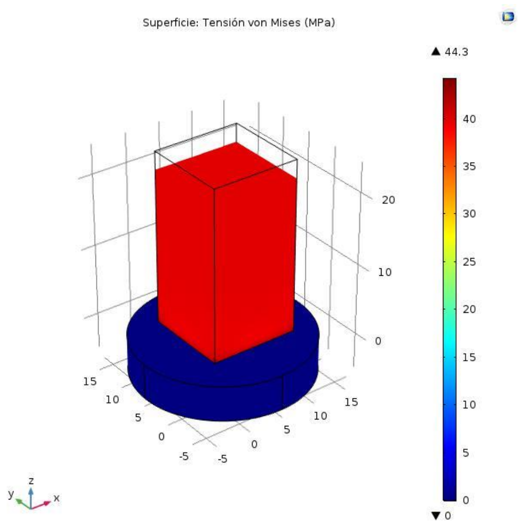

Figure 5. FEM results for the isotropic material.

The orthotropic material has been evaluated using the E_{ij} and G_{ij} modulus of Table 1 and the Poisson ratio υ_{ij} =0.025. The FEM results are tabulated in Table 4, while Fig. 6 plot the Von Misses stress of compression.

Table 4: Results for the orthotropic model (*z* direction) of the 30% C.F. reinforced material.

FEM [MPa]	**Yield** [MPa]	**Relative error**
50	42.97	16.4 %

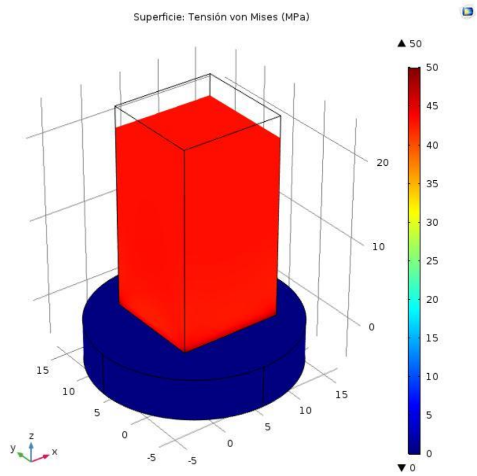

Figure 6. FEM results for the orthotropic material.

Moreover, two different reinforced materials with 17% and 47% volume of fiber have been simulated, using the previous computational model for an orthotropic material. Table 5 presents the simulation results for these reinforced materials. The von Mises stresses are plotted in Fig. 7 and Fig. 8, for the 17% volume of fiber and 47% volume of fiber, respectively.

Table 5: Orthotropic model simulation results.

Material (volume of fiber, %)	**FEM** [MPa]	**Yield** [MPa]	**Relative error**
17	45.13	40.03	12.7 %
47	61.8	53.30	15.9%

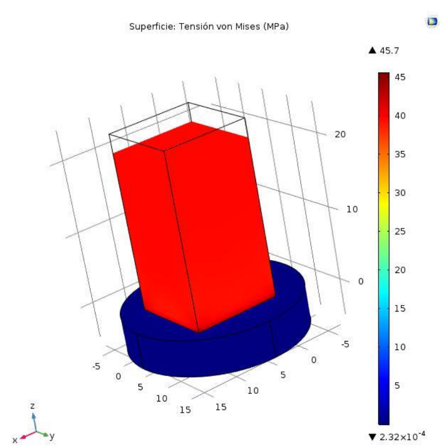

Figure 7. FEM results for the orthotropic material, 17% reinforced volume.

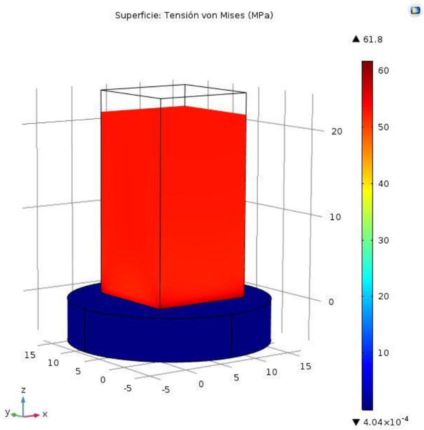

Figure 8. FEM results for the orthotropic material, 47% reinforced volume.

7. Analysis of results and conclusions.

To improve the simulation results we have had to reduce the analytical Poisson ratio to a value of 0.025, obtaining a final relative error of 3.09%, approximately. The computational results for the orthotropic model of a 3D printed reinforced material give a relative error of 16.4%. However, the reinforced polymer present several factors affecting its mechanical behavior, for example the distance between extruded filaments, width, filament pattern, layer thickness, etc. (Domingo-Espin *et al*., 2015). Therefore, we consider that for this complex material, the previous error gives an acceptable simulation concerning the mechanical performance of a 3D printed reinforced material. Further simulations for a prototype pylon have been developed, showing that the prototype exceed the yield point (42.03 MPa) of material, needing a redesign or a topology optimization of part, as the Von Misses stresses of Fig. 9 show. The simulation of fiber reinforced materials is a challenging task. The isotropic model presented a lower error, however the orthotropic model is a better method for analyzing the mechanical performance of reinforced materials.

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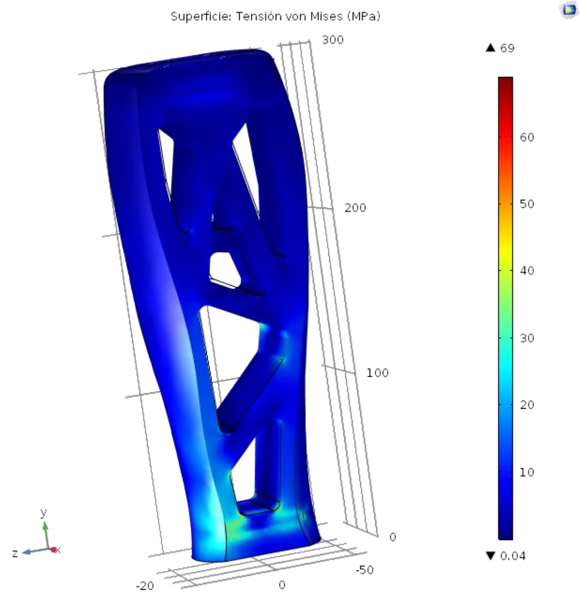

Figure 9. FEM results for the heel strike of a pylon prototype, using orthotropic model material, 30% reinforced volume.

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